Title: Verification and characterization of a fracture network within the Maquoketa Shale confining unit, southeastern Wisconsin

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Background/Need: The Maquoketa Formation, a dolomitic shale, forms the most important aquitard in eastern Wisconsin, USA, isolating the water-table and Silurian aquifers from the underlying Cambrian-Ordovician aquifer. The hydraulic properties of the Maquoketa aquitard are of interest for input to a regional groundwater flow model, which will be used for better groundwater resource management and wellhead protection.

Analysis of earlier results showed that while the Maquoketa Formation has very low rock-matrix hydraulic conductivity, simultaneous drawdowns occurred at multiple levels within this formation when the overlying Silurian aquifer was pumped. Such observations violate equivalent porous medium assumptions but they can be explained by local vertical fracture interconnections between the observed bedding-plane fractures within the Maquoketa Formation.

Objectives: The objective of the additional fieldwork described in this report was to characterize hydraulic and transport properties of a potential fracture network extending from the Silurian dolomite aquifer into the Maquoketa Formation. If significant vertical fracture interconnections exist, they could result in much higher bulk hydraulic conductivity in the upper Maquoketa Formation. The observed vertical head distribution showed that almost half of the total vertical head loss due to regional pumping occurs across the lower contact of the formation, which is not consistent with a homogeneous, very low-conductivity aquitard at steady-state with the heads in the adjacent aquifers.

Methods: Therefore, we proposed the use of more specialized methods, better suited to fractured rock characterization, to investigate the hydraulic properties and interconnectivity of discrete transmissive fractures in the Maquoketa Formation. These methods consist of short-interval packer testing and tracer experiments, which were conducted using wells at the DOT field site in Waukesha County. Preliminary geochemical and isotopic analysis of water samples showed no significant trends with depth, and a more comprehensive analysis is presented in this report.

Results and Discussion: The highest values of hydraulic conductivity are associated with the upper part of the Maquoketa Formation, where bedding-plane fractures associated with dolomitic beds had previously been identified. There is a broad range of values over almost 5 orders of magnitude, which results from the high transmissivity of these bedding-plane fractures, present in only some of the intervals tested. One five-foot interval that contained numerous small-aperture fractures is connected to a larger transmissive network, and yielded a sustainable pumping rate causing drawdown in other wells.

Water samples showed primarily calcium-magnesium-bicarbonate geochemistry, with sodium and sulfate more abundant in parts of the Maquoketa Formation. Variation in electrical conductivity and concentrations of major ions with depth was significant. We found no tritium, but high levels of strontium, normally a trace constituent, in water from the Maquoketa Formation. Convergent-flow tracer experiments were conducted using heated water, but no breakthrough (increase in temperature) was recorded by in-situ instrumentation in the Maquoketa Formation. However, drawdown observed in different wells due to pumping during these long-duration tracer tests was analyzed to estimate transmissivity of the fracture system.

Conclusions/ Implications/ Recommendations: The hydrogeology of the Maquoketa Formation is determined by significant geologic heterogeneity. This heterogeneity consists primarily of transmissive bedding-plane fractures, which are associated with interbedded shale and dolomite facies in the upper part of the formation. Oxygen and deuterium isotope data, and the lack of tritium shows that groundwater in the Maquoketa Formation is not modern and may date in part to Pleistocene times. The major ion chemistry plots along mixing trends, between endpoints interpreted to be characteristic of water in fractures and rock pores. The heterogeneity of water chemistry and variation in field-measured hydraulic conductivity are consistent with a three-dimensional flow system controlled by transmissive fractures within the aquitard.

Water chemistry and isotope data, and tracer tests indicate that no significant vertical flow occurs between the Silurian aquifer and Maquoketa Formation, although limited vertical interconnections may exist between bedding-plane fractures. The lateral continuity of the transmissive bedding-plane fractures and limited vertical interconnections increase the bulk hydraulic conductivity of the dolomitic upper part of the Maquoketa Formation. The current transient head field in the Maquoketa Formation coupled with the uniformly low hydraulic conductivity of the base of the formation account for the hydraulic effectiveness of this aquitard. However, the top of the Maquoketa Formation cannot be assumed to be virtually impermeable to contaminants, for example DNAPLs, whose migration is not dependent on head gradients.

Related Publications: Eaton, T.T. 2002. *Fracture heterogeneity and hydrogeology of the Maquoketa aquitard, southeastern Wisconsin*. unpublished Ph.D. dissertation (Geology and Geophysics), University of Wisconsin-Madison, 200 p.

Key words: Maquoketa, aquitard, fractures, heterogeneity

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Final Report: A final report containing more detailed information on this project is available for loan at the Water Resources Institute, University of Wisconsin-Madison, 1975 Willow Drive, Madison, Wisconsin 53706. (608) 262-3069.